

APPENDIX B: CARBON DIOXIDE CAPTURE TECHNOLOGY SHEETS

# ADVANCED COMPRESSION



# NOVEL CONCEPTS FOR THE COMPRESSION OF LARGE VOLUMES OF CO<sub>2</sub>

## primary project goals

Southwest Research Institute (SwRI) is developing novel compression technology concepts to reduce carbon dioxide (CO<sub>2</sub>) compression power requirements by 10 percent compared to conventional compressor designs. The basic concept is a semi-isothermal compression process where the CO<sub>2</sub> is continually cooled using an internal cooling jacket rather than using conventional interstage cooling. The project has completed thermodynamic (Phase I) and prototype testing (Phase II). A full-scale demonstration of a multi-stage, internally cooled diaphragm pilot test program (Phase III) is well underway.

## technical goals

### Phase III

- Design and construct a pilot-scale demonstration of a multi-stage internally cooled compressor diaphragm design.
- Complete a comprehensive thermodynamic and cost analysis of both pulverized coal (PC) and integrated gasification combined cycle (IGCC) plant incorporating the new compression technology.
- Design a multi-stage diaphragm and test loop.
- Design, fabricate, and test a third-generation cooled diaphragm and test in a single-stage test rig.

## technical content

In the cooled diaphragm concept, the gas is continually cooled after each stage in the flow path through the compressor. A cooling jacket insert is used in the diaphragm of each stage to provide continuous cooling. Figure 1 shows a conceptual design for an internally cooled compressor. The flow of the CO<sub>2</sub> is shown in red, while the cooling liquid is shown in blue.

SwRI examined a number of different compression options to find the ones that would consume the least amount of power. Figure 2 shows how two hypothetical compression processes can achieve the same pressure, but still consume different quantities of power. The isothermal compression, even at 60 percent efficiency, requires less power than the isentropic compression at 100 percent efficiency. Therefore, efficiency alone cannot be used as a figure of merit for the compression process.

Figure 3 shows the pressure/enthalpy curves for six of the options examined by SwRI. While liquefaction and pumping is a viable option and may be superior to a pure compression route in cold climates, the semi-isothermal compression proved to be superior when all of the heat exchanger performance and other losses were taken into account.

Table 1 presents a description of the compression and cooling technology options and the resultant power requirements for the U.S. Department of Energy (DOE) 550-megawatt (MW) PC reference power plant with carbon capture using an amine process (≈1.3 million lb/hr CO<sub>2</sub> stream). The results show an almost 10 percent power savings when using the cooled diaphragm technology over a conventional inline compressor, and even shows

technology maturity:

Pilot-Scale, 90 tonnes/hr

project focus:

Evaluation of Compression Efficiency Improvements

participant:

Southwest Research Institute

project number:

FC26-05NT42650

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partners:

Dresser-Rand

performance period:

9/28/05 – 12/31/13

greater performance than an integrally geared compressor for higher ambient temperatures (not shown). The integrally geared compressor contains eight stages, while the inline compressor represents 13 stages (6/7) between the two bodies. The cooled diaphragms are modeled with different heat exchanger effectiveness values. Values between 15 and 30 percent were measured in the Phase II single-stage test program, depending on the operating condition. The second-generation design for the multi-stage cooled diaphragm is predicted to be in the 15 to 20 percent range. A third-generation concept is currently under development with the goal of greater than 30 percent effectiveness. A final case shows the benefit of additional stages (7/8) on the cooled diaphragm performance. Representative stage efficiencies were used from actual selections in both cases and gearbox losses are taken into account where appropriate. Through the Phase III development program, a high-pressure version of the cooled diaphragm has been developed, making it viable in both the low- and high-pressure compressor bodies.

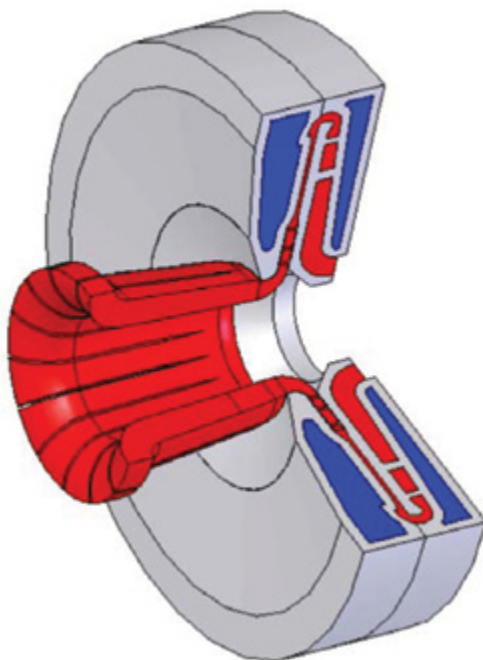


Figure 1: Design for an Internally Cooled Compressor

### Required Compression Power: Path-Dependency of Compression Process

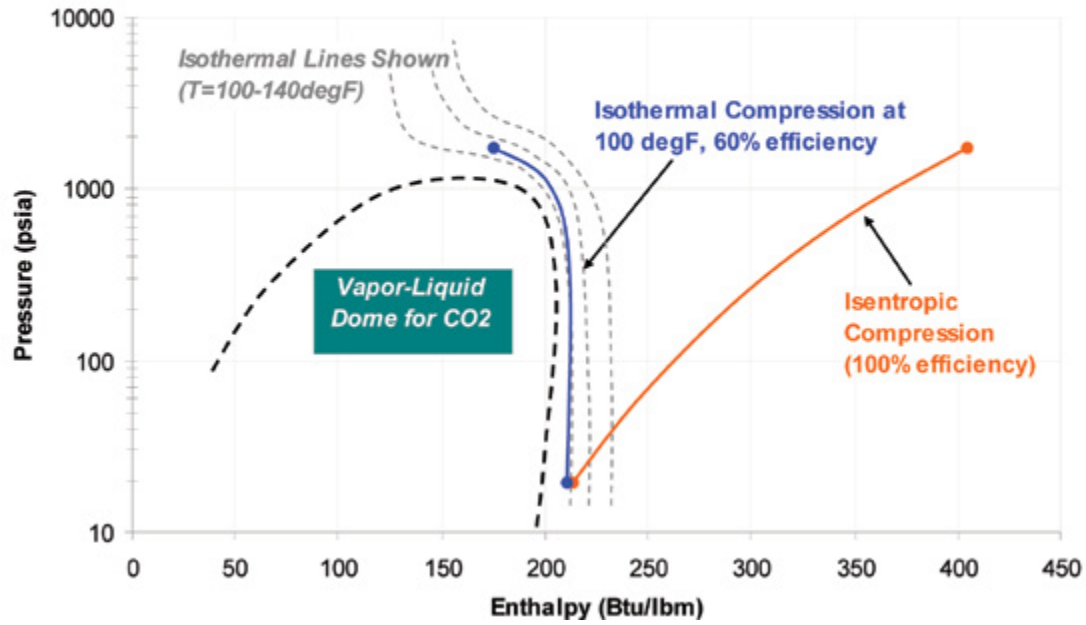


Figure 2: Example of Path Dependency of Compression Power

### Compression Technology Options for IGCC Waste Carbon Dioxide Streams

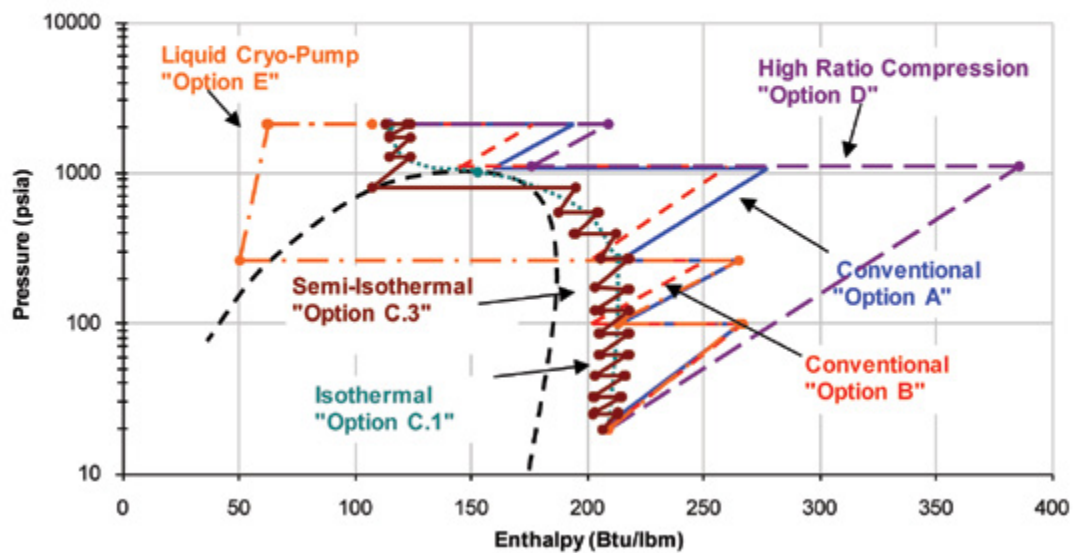


Figure 3: Required Compression Power for the Investigated Technology Options

TABLE 1: SUMMARY OF COMPRESSOR PREDICTIONS FOR DOE REFERENCE PC PLANT WITH CARBON CAPTURE

| Configuration  | Compression Power (MW) | Total Plant Power (MWe) | % of Power for CO <sub>2</sub> Compression | % Power Reduction From Cooled Diaphragms <sup>2</sup> |
|--|------------------------|-------------------------|--|---|
| 8-Stage Integrally Geared Centrifugal                          | 56.3                   | 550                     | 10.2%                                      | -   |
| 6/7-Stage Inline Centrifugal                                   | 63.9                   | 550                     | 11.6%                                      | -   |
| 6/7-Stage Inline Centrifugal w/15% Effective Cooled Diaphragms | 62.0                   | 550                     | 11.3%                                      | 3.0%  |
| 6/7-Stage Inline Centrifugal w/25% Effective Cooled Diaphragms | 60.7                   | 550                     | 11.0%                                      | 5.0%  |
| 6/7-Stage Inline Centrifugal w/35% Effective Cooled Diaphragms | 59.5                   | 550                     | 10.8%                                      | 6.9%  |
| 8/9-Stage Inline Centrifugal w/35% Effective Cooled Diaphragms | 58.1                   | 550                     | 10.6%                                      | 9.1%  |

Figure 4 shows a photograph of the internally cooled compressor diaphragm from the Phase II program, which routes cooling fluid through the diaphragm to remove the heat of compression. This prototype was installed into a closed-loop compressor test facility at SwRI and tested for a range of speeds, flows, pressures, and cooling fluid conditions. The testing agreed with computational fluid dynamics (CFD) predictions for the heat transfer characteristics. Figure 5 shows a comparison between measured and predicted heat exchanger effectiveness for the diaphragm, which shows good agreement. Unlike external heat exchangers, no additional pressure drop occurs between stages.

Under the Phase III effort, the design of the new test loop and multi-stage compressor diaphragms is complete. Manufacturing is underway on the compressor package being supplied by Dresser-Rand and is scheduled to arrive at SwRI in late June 2013. Procurement of all hardware for the test loop is underway and will be installed in time for the compressor arrival. Commissioning and testing of the unit will be carried out through the remainder of the year.

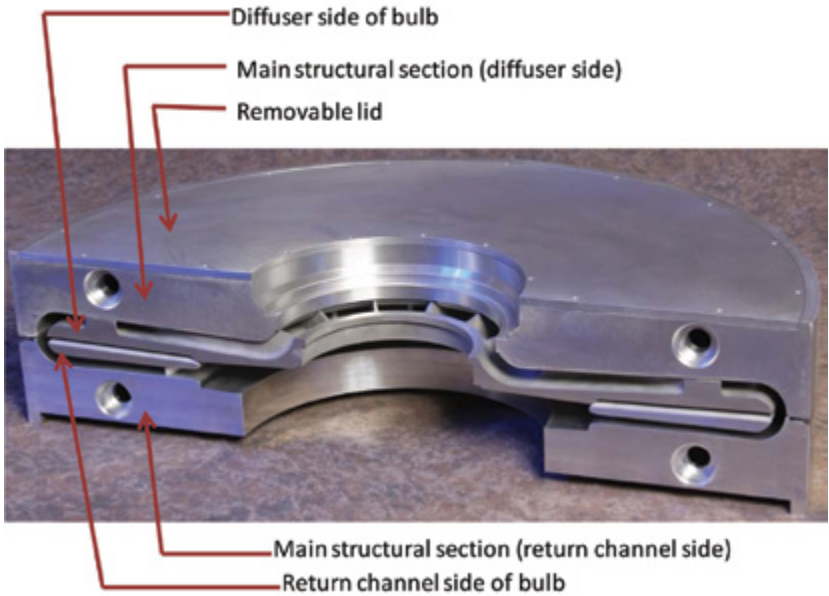


Figure 4: Internally Cooled Compressor Diaphragm

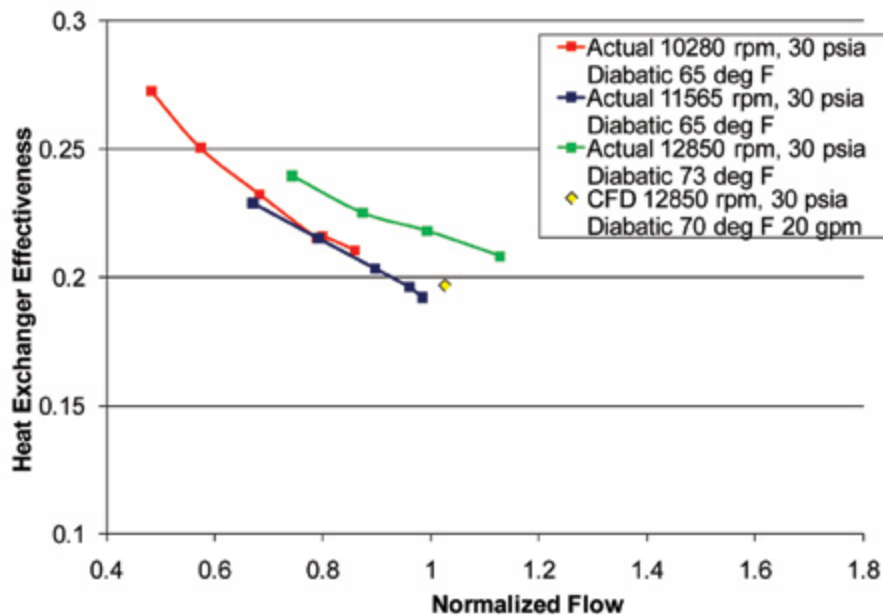


Figure 5: Heat Transfer Effectiveness of CFD and Test Results

### technology advantages

- New compression process could use up to 10 percent less power compared to commercially available inline centrifugal compressors.
- Applicable to all types of power plants, including PC, IGCC, and oxy-fuel.
- Could result in significant capital savings and reliability improvement compared to an integrally geared compressor.
- Inline compressors are scalable to large power plants, and their reliability is well proven in LNG and Ethylene service.

### R&D challenges

- There will be a wide range of CO<sub>2</sub> output from the power plant based on required electrical output.
- Carbon dioxide compression technology must have high reliability.
- IGCC plants contain multiple CO<sub>2</sub> streams at different pressures.
- The volume reduction during the compression can exceed 500:1.

### results to date/accomplishments

- Development complete of multi-stage internally cooled diaphragm.
- Detailed design of Dresser-Rand DATUM compressor with multi-stage cooled diaphragms is complete.
- Design of a closed loop to test back-to-back compressor is complete.
- All long-lead hardware items have been placed on order.

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- Installation of major equipment.
- Measurement of the CO<sub>2</sub> baseline compressor performance (no cooling).
- Measurement of the CO<sub>2</sub> compressor performance with diaphragm cooling.
- Perform a third-generation cooled diaphragm test in single-stage test rig.
- Final test results will not be available until the first quarter of 2014.

#### available reports/technical papers/presentations

Moore, J.J.; et al., “Advance Centrifugal Compression and Pumping for CO<sub>2</sub> Applications,” presented at the 2012 NETL CO<sub>2</sub> Capture Technology Meeting, July 2012.

<http://www.netl.doe.gov/File%20Library/Events/2012/CO2%20Capture%20Meeting/J-Moore-SRI-CO2-Compression.pdf>.

Moore, J.J.; et al., “Novel Concepts for the Compression of Large Volumes of CO<sub>2</sub>,” presented at the 2010 NETL CO<sub>2</sub> Capture Technology Meeting, Pittsburgh, Pennsylvania, September 2010. <http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/co2/Jeffery-Moore---NT42650.pdf>.

Moore, J.J.; et al., “Novel Concepts for the Compression of Large Volumes of CO<sub>2</sub> – Phase II,” presented at the Annual NETL CO<sub>2</sub> Capture Technology for Existing Plants R&D Meeting, Pittsburgh, Pennsylvania, March 2009. <http://www.netl.doe.gov/publications/proceedings/09/CO2/pdfs/42650%20Southwest%20Research%20compression%20%28Moore%29%20mar09.pdf>.



# THERMAL INTEGRATION OF CO<sub>2</sub> COMPRESSION PROCESSES WITH COAL-FIRED POWER PLANTS EQUIPPED WITH CARBON CAPTURE

technology maturity:

Systems Analysis Models

project focus:

Thermal Integration of CO<sub>2</sub> Compression

participant:

Lehigh University

project number:

FE0002146

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partners:

none

performance period:

10/1/09 – 6/29/12

## primary project goals

Lehigh University set out to use systems analysis models to study the benefits of improved thermal integration for coal-fired power plants equipped with post- or oxy-combustion carbon dioxide (CO<sub>2</sub>) capture systems.

## technical goals

- Gather technical and performance information from compressor manufacturers and the technical literature in order to calculate compressor power requirements, performance of interstage heat exchangers, and interstage pressure drops.
- Develop and validate ASPEN Plus models of coal-fired power plants with solvent-based post-combustion CO<sub>2</sub> capture to simulate the effects of different thermal integration options on power plant efficiency and net power output.
- Develop and validate ASPEN Plus models of oxy-combustion coal power plants to simulate the effects of different thermal integration options on power plant efficiency and net power output.

## technical content

Coal-based power plants equipped for CO<sub>2</sub> capture require a compression system to increase the pressure of the CO<sub>2</sub> to the level needed for geological storage (approximately 2,200 pounds per square inch absolute [psia]). In addition to its relatively high capital cost, the CO<sub>2</sub> compression system requires a significant amount of auxiliary power for operation. The technology options available for CO<sub>2</sub> compression include:

- A multistage, in-line centrifugal compressor with interstage and post-compression cooling.
- A multistage, integrally geared centrifugal compressor with interstage cooling.
- A multistage, supersonic shock wave compressor with interstage and post-compression cooling.
- A compression process involving gas phase compression to approximately 200 psia, cryogenic cooling through the two-phase region, and increase in pressure of the liquid CO<sub>2</sub> to the final pressure using a liquid cryogenic pump.

For some of these technology options, there is the potential for utilization of waste heat from the CO<sub>2</sub> compressors within the power plant. This project used first-principle engineering analyses and computer simulations to determine the increase in power output and improvement in net unit heat rate which could occur by thermal integration of the CO<sub>2</sub> compression process with the CO<sub>2</sub> capture system, boiler, and turbine cycle. The study



included gathering information on compressor type and compressor stage efficiencies. The aerodynamic conditions and the flow geometry change from the low-pressure to high-pressure end of the compressor typically result in variations in isentropic stage efficiency from inlet to outlet. Correct values for isentropic stage efficiency are needed in order to obtain realistic values of compressor power and CO<sub>2</sub> exit temperature for each stage; values of stage efficiency provided by compressor vendors were used in this project. In addition, analyses were performed to estimate CO<sub>2</sub> and cooling fluid stage exit temperatures as functions of coolant inlet temperature and flow rate. While the literature suggests that most CO<sub>2</sub> compressors are air-cooled, analyses were performed assuming the use of water-cooled heat exchangers for interstage cooling and effective utilization of compressor waste heat.

Results from the compressor simulations were linked to models of the power plant for analysis of various thermal integration options. The compressor and power plant simulations were performed using the ASPEN Plus software. Each of the following cases were analyzed using bituminous, Powder River Basin (PRB), and lignite coals:

- Pulverized coal-fired boiler with post-combustion, solvent-based capture systems using a generic monoethanolamine (MEA) scrubber.
- Oxy-combustion pulverized coal boiler.

The thermal integration options that were considered include pre-drying of low-rank coals, regeneration of CO<sub>2</sub> solvent, and boiler feedwater preheating. Table 1 presents the matrix of analyses that were performed.

**TABLE 1: SYSTEMS ANALYSIS MATRIX FOR CO<sub>2</sub> COMPRESSION HEAT INTEGRATION**

| Use of Recovered Heat from CO <sub>2</sub> Compressor       |                       |                                    |                          |
|---|-----------------------|------------------------------------|--------------------------|
| Integration Method  | Pre-Dry Low-Rank Coal | Regenerate CO <sub>2</sub> Solvent | Preheat Boiler Feedwater |
| <b>Post-Combustion Solvent-Based CO<sub>2</sub> Capture</b> |                       |                                    |                          |
| Bituminous  | No                    | Yes                                | Yes                      |
| PRB   | Yes                   | Yes                                | Yes                      |
| Lignite   | Yes                   | Yes                                | Yes                      |
| <b>Oxy-Combustion</b>                                       |                       |                                    |                          |
| Bituminous  | No                    | No                                 | Yes                      |
| PRB   | Yes                   | No                                 | Yes                      |
| Lignite   | Yes                   | No                                 | Yes                      |

### technology advantages

- Determine the best way to utilize waste heat from CO<sub>2</sub> compression.
- Improve power plant efficiency and increase the net power output.
- Reduce capital and operating cost for CO<sub>2</sub> capture and compression systems.

### R&D challenges

- Implementation of the thermal integration opportunities as cost-effective technology options.

### results to date/accomplishments

- Completed compressor performance analyses.
- Completed analyses of the various thermal integration options for both the post- and oxy-combustion capture technologies. The results show that potential heat rate improvements are sensitive to the type of compressor, type of coal, and thermal integration option. In the case of oxy-combustion capture, the predicted reductions in heat rate range from 2.0 to 8.4 percent; for MEA post-combustion capture, they range up to 10.45 percent.

[next steps](#)

This project ended on June 29, 2012.

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[available reports/technical papers/presentations](#)

Levy, E. "Thermal Integration of CO<sub>2</sub> Compression Processes with Coal-Fired Power Plants Equipped with Carbon Capture," Lehigh University Final Technical Report, DOE Project DE-FE0002146, October 2012.

Levy, E.; Jonas, G.; and Martin, E. "Thermal Integration of Waste Heat in Coal-Fired Units with Post-Combustion Carbon Capture," Proceedings 37<sup>th</sup> International Conference on Clean Coal and Fuel Systems, Clearwater, Florida, June 2012.

Levy, E.; Charles, J.; Jonas, G.; Aiken, E.; and Martin, E. "Thermal Integration of CO<sub>2</sub> Compression Heat to Improve Power Plant Heat Rate," Poster Presentation at 2012 NETL CO<sub>2</sub> Capture Meeting, Pittsburgh, Pennsylvania, July 2012.

Levy, E.; and Charles, J. "Use of Recovered CO<sub>2</sub> Compression Heat to Improve Heat Rates of Oxy-Fired Units," Proceedings Eleventh Annual Conference on Carbon Capture and Sequestration, Pittsburgh, Pennsylvania, May 2012.

Levy, E.; Charles, J.; Jonas, G.; Aiken, E.; and Martin, E. "Thermal Integration of CO<sub>2</sub> Compression Heat to Improve Power Plant Heat Rate," Poster Presentation at 2011 NETL CO<sub>2</sub> Capture Meeting, Pittsburgh, Pennsylvania, August 2011.

Levy, E.; Jonas, G.; and Zubernis, J. "CO<sub>2</sub> Compressors with Interstage Cooling for CCS Applications: Effects of Compressor Type," Proceedings 36<sup>th</sup> International Conference on Clean Coal and Fuel Systems, Clearwater, Florida, June 5-9, 2011.

Levy, E.; Martin, E.; Aiken, E.; and Charles, J. "Thermal Integration of Heat Captured From Compressor Intercoolers for Improved Unit Heat Rate," Proceedings Tenth Annual Conference on Carbon Capture and Sequestration, Pittsburgh, Pennsylvania, May 2-5, 2011.

# RAMGEN SUPERSONIC SHOCK WAVE COMPRESSION AND ENGINE TECHNOLOGY

## primary project goals

Ramgen Power Systems is designing and developing a unique compressor technology based upon aerospace shock wave compression theory for use as a carbon dioxide (CO<sub>2</sub>) compressor. A shock wave-based gas turbine engine is also being developed.

## technical goals

### Phase I

- Complete testing of a high-pressure ratio (8:1) air compressor rotor for the Ram 2 Program.
- Demonstrate the feasibility of high-pressure shock wave compression.
- Develop and detail a viable commercialization path.

### Phase II

- Perform critical success factors risk reduction validation and test program to identify and reduce technical risk areas.
- Complete general design and demonstration of a CO<sub>2</sub> supersonic shock compressor approximately 13,000 hp in size.
- Complete design, build, and test of multiple engine builds to demonstrate supersonic shock compression and advanced vortex combustion in an engine embodiment.

## technical content

### Shock Wave CO<sub>2</sub> Compressor

Ramgen Power Systems is developing a supersonic shock wave compression technology, similar in concept to an aircraft's ramjet engine, for use in a stationary compressor. Ramgen's compressor design, known as a Rampressor, features a rotating disk that operates at high peripheral speeds to generate shock waves that compress the CO<sub>2</sub>. Compared to conventional compressor technologies, shock compression offers several potential advantages: high compression efficiency; high, single-stage compression ratios; opportunity for waste heat recovery; and low capital cost. For example, Ramgen's shock compression has the potential to develop compression ratios from 2.0 to 15.0 per stage with an associated adiabatic efficiency of 85 to 90 percent. For CO<sub>2</sub> applications, Ramgen anticipates using a nominal, two-stage 100:1 compression ratio, featuring a matched pair of 10:1 compression stages with an intercooler located between the stages. Prototype testing completed in 2007 achieved a 7.8:1 compression ratio.

When shock waves pass through a gas, they cause a localized compression. Figure 1 shows that the rotating rotor rim has small, shallow angles which, when rotating at high speeds, will produce supersonic shock waves both prior to and post-peak. These shock waves, modeled in the 3-D Euler Computational Fluid Dynamics (CFD) image shown, are first oblique,

### technology maturity:

Pilot-Scale,  
1,680 Tonnes/Day CO<sub>2</sub>

### project focus:

Shock Wave Compression

### participant:

Ramgen Power Systems

### project number:

FE0000493  
FC26-06NT42651

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### partners:

Dresser-Rand

### performance period:

5/10/2006 – 6/30/2014

then normal. Additionally, strakes (ridges) are incorporated into the design of the rotor to form sidewalls. The strakes are utilized as shock compression ducts, as well as to separate high-pressure discharge from low-pressure suction. The combination of shocks and strakes result in a compressed fluid delivered from a stationary discharge duct with compression efficiencies comparable to conventional industrial turbo-compressors, but with much higher single-stage pressure ratios and therefore higher quality heat of compression that combine to deliver significant installed and operational cost savings versus existing turbo-compressors.

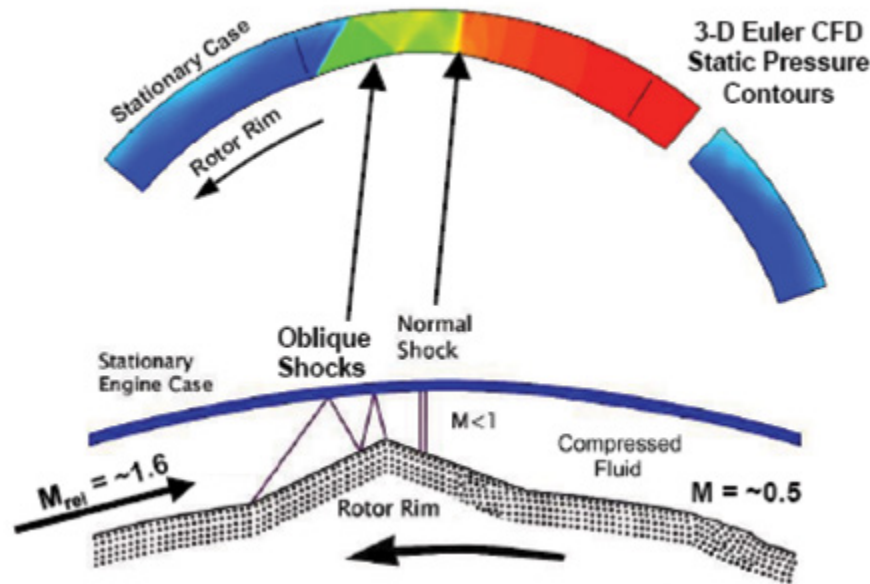


Figure 1: Schematic of Rotor Rim and Engine Case and 3-D Euler CFD Image Depicting Shock Wave Behavior

Two stages of compression are used with an intercooler located between the stages to optimize the efficiency of the compression process. Figure 2 shows the energy required as shaft work and the thermal energy lost to the cooling stream for a 200-MW coal plant with 90 percent CO<sub>2</sub> capture. The numbers found in the figure represent a stage in the process; each stage is driven independently through an external gearbox.

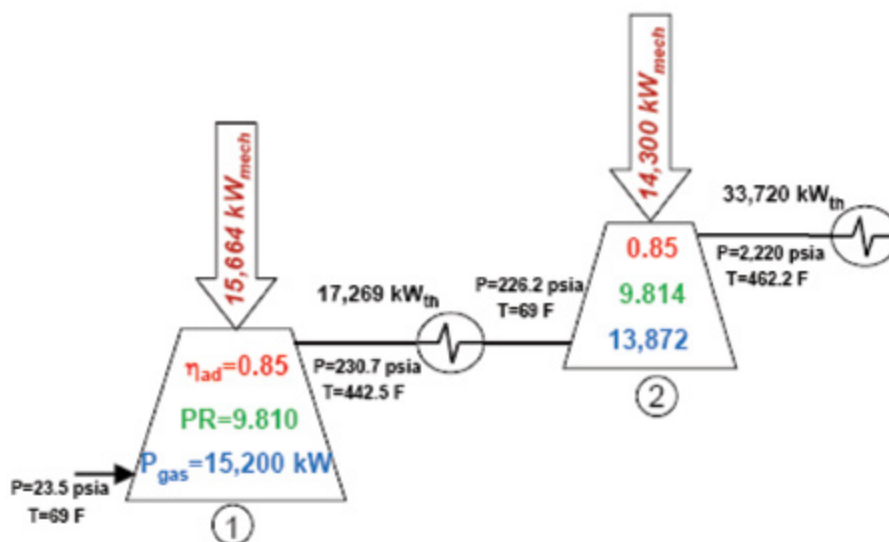


Figure 2: Series Process Schematic

As seen in Figure 2, the total shaft power is 29,964 kW<sub>mech</sub>, which corresponds to a heat of compression of 50,989 kW<sub>th</sub>. Approximately 28,986 kW<sub>th</sub> of the heat of compression lost is recoverable down to 93°C (200°F).

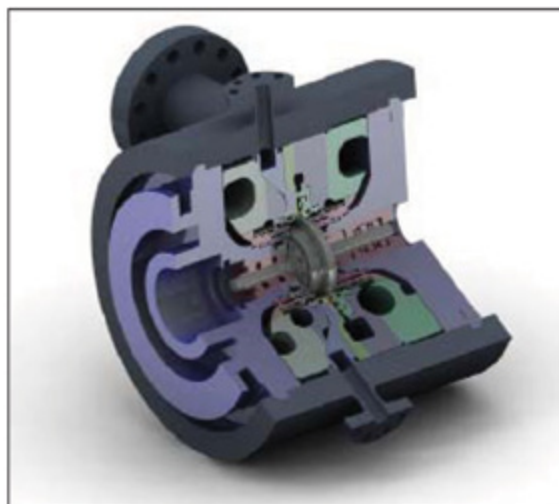


Figure 3: Cross Sectional Model of a 1/10<sup>th</sup> Scale Single-Stage Supersonic Shock Wave Compressor

### Shock Wave Gas Turbine Engine

Ramgen is also developing a unique shock wave-based gas turbine engine that is expected to significantly improve energy efficiency. The Ramgen Integrated Supersonic Component Engine (ISCE) consolidates the compressor, combustor, and turbine of a conventional gas turbine into a single wheel that operates based on the same Brayton thermodynamic cycle as a conventional gas turbine; however, the mechanical implementation of the process is quite different. One important advantage is that because the compression, combustion, and expansion processes are all integrated into a single, constant speed rotor, there is no physical acceleration of the rotating components required as the system transitions from idle to full power. The output torque and power are modulated from the full-speed, no-load condition to the full-speed, full-power condition by adjusting the fuel flow. As a result, the system can transition from idle to full power as quickly as the fuel flow can be adjusted. Testing has demonstrated a transition from combustor heat release levels consistent with a power variation from idle (pilot fuel only) to full power (full fuel/air premix) in periods as short as 150 to 200 milliseconds (ms). The ISCE will have the ability to load follow from idle to full power in time scales as short as a few hundred ms compared with a response rate of 7 to 10 seconds for most intermediate-sized gas turbine electric power generating systems.

The initial proof of concept Ramgen engine used an un-shrouded rotor configuration mounted on a single high-speed shaft driving a generator/starter motor through a speed-reducing gearbox. The ISCE system will incorporate a fully shrouded flowpath power-wheel configuration. The reduced size of the components will result in a significantly more compact, lightweight, low-cost generation system compared to any other conventional turbo-generator system. One embodiment of this integrated power-wheel system is illustrated in Figure 4 and shows the engine feature of a propulsive flowpath that is fully shrouded and formed by a series of nested rim segments supported by a metal-matrix or polyimide composite outside diameter support ring.

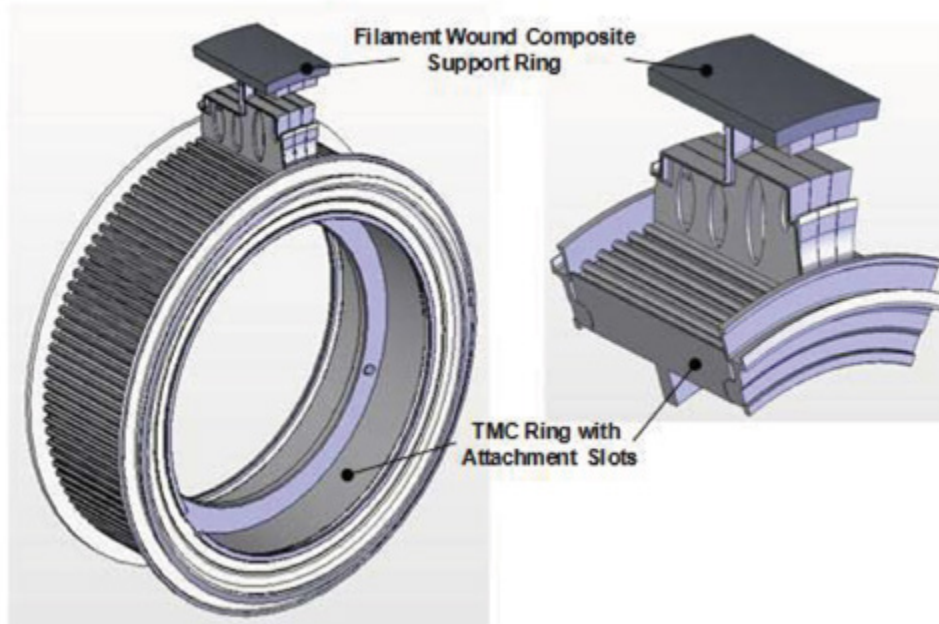


Figure 4: Cross Sectional Model of a 1/10<sup>th</sup> Scale Single-Stage Supersonic Shock Wave Compressor

### technology advantages

- Competitive operating efficiency and reduced installed capital cost (approximately 50%) over multi-stage bladed turbo compressors.
- High-stage discharge temperature enables cost-effective recovery of heat of compression.
  - Improves carbon capture and sequestration (CCS) efficiency.
  - Reduces power plant de-rate.

### R&D challenges

- Complicated shock wave aerodynamics on the flowpath requires intensive computing capabilities and model development.
- High rotational speeds and the resulting stresses can result in expensive rotor manufacturing techniques.
- High-pressure ratio compressors yield high rotor thrust loads on bearings and structure.

### results to date/accomplishments

- ISCE final design completed.
- Full-speed test rotor runs completed.
- Carbon dioxide compressor and ISCE test (Build 1) equipment have initiated testing under full-speed operations.

### next steps

Complete Build 2 compressor design.

- Complete Build 2 engine design.
- Complete Advanced Vortex Combustor sub-component design, build, and test.



- Improve understanding of the supersonic aerodynamics needed to achieve product performance levels in the CO<sub>2</sub> compressor and engine compressor.
- Continue to develop high-speed performance computing capability at Oak Ridge National Laboratory.
- Complete 13,000 hp CO<sub>2</sub> compressor and ISCE testing.

[available reports/technical papers/presentations](#)

Lupkes, K., “Ramgen Supersonic Shock Wave Compression and Engine Technology,” presented at the 2012 NETL CO<sub>2</sub> Capture Technology Meeting, Pittsburgh, Pennsylvania, July 2012 <http://www.netl.doe.gov/publications/proceedings/12/co2capture/presentations/3-Wednesday/K%20Lupkes-Ramgen-Shockwave%20Compression.pdf>.

Grosvenor, A.D.; Zheltovodov, A.A.; Derunov, E.K.; 2012; “Numerical Prediction of 3D Shock-Induced Turbulent Flow Separation Surrounding Bodies of Revolution Adjacent to a Flat Surface,” EUCASS Book Series on Advances in Aerospace Sciences, Progress in Flight Physics, Eds. Ph. Reijasse, D. Knight, M. Ivanov, and I. Lipatov, Torus Press, ISBN/ISSN: 978-2-7598-0674-4, pp. 119-140.

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Grosvenor, A.D.; Zheltovodov, A.A.; Matheson, M.A.; Sailer, L.M.; Krzysztopik, M.; Gutzwiller, D. P.; 2011; “Verification for a Series of Calculated 3D Shock Wave/Turbulent Boundary Layer Interaction Flows,” Proceedings 4<sup>th</sup> European Conference for Aerospace Sciences (EUCASS 2011). July 4-8, 2011, Saint Petersburg, Russia. Paper 578.

Lawlor, S., “CO<sub>2</sub> Compression Using Supersonic Shock Wave Technology,” presented at the 2010 NETL CO<sub>2</sub> Capture Technology Meeting, Pittsburgh, Pennsylvania, September 2010. <http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/co2/Shawn-Lawlor---Ramgen-Power-Systems.pdf>.

Grosvenor, A.D.; Zheltovodov, A.A.; Derunov, E.K.; 2010; “SWBLI Calculations in Conditions of Aerodynamic Interference of Two Bodies of Revolution with a Flat Surface,” ICMAR, Novosibirsk, Russia.

Lawlor, S., “CO<sub>2</sub> Compression Using Supersonic Shock Wave Technology,” presented at the Annual NETL CO<sub>2</sub> Capture Technology for Existing Plants R&D Meeting, Pittsburgh, Pennsylvania, May 2009. <http://www.netl.doe.gov/File%20Library/Research/Coal/ewr/co2/42651-Ramgen-compression--Lawlor--mar09-public-version.pdf>.

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Grosvenor, A.D., 2007, “RANS Prediction of Transonic Compressive Rotor Performance Near Stall,” Turbo Expo 2007 Montreal, GT2007-27691.

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